An Ab Inito Study: The effects of water complexation on the vibrational frequencies of glycine conformer 2

Bridgit Crews

Organisms are made up of a complex organization of unique proteins, which together perform a multitude of specialized tasks. Upon closer inspection of these seemingly intelligent mini-life forms one finds they are merely strings of smaller subunits in various orders and conformations. Due to this confoundingly simple arrangement of structure and sequence, life as we know it exists. These subunits are amino acids and necessarily, to gain better insight into the microscopic workings of living organisms we must look at the chemical nature of these pieces and what alterations they adopt under different environmental conditions. In spectroscopic studies it is possible to look at amino acids and peptides singularly without complicating solutions or averaging ensembles. However, by viewing amino acids or peptides singularly, and not in solution, we may lose some information about their nature in a normal biological environment. For example, it is known that a barrier to intramolecular proton transfer exists for glycine upon addition of solvent molecules and thus glycine zwitterion exists as a minimum in solution but not in gas. [4] In the present study we are interested in how complexation with water may shift the vibrational frequencies of amino acids. This data may complement spectroscopic studies of amino acids or peptides in water clusters and may also prove helpful in identifying amino acids on ice grains in the interstellar medium.

During the initial studies that mapped the potential energy surface of glycine there was some discrepancy on whether non-ionized conformer 2 was indeed a minimum. This seemed to be a product of basis set choice and eventually it was concluded that the non-planar form of conformer 2 was indeed a minimum and lower in energy than the planar form.[1, 2, 3] Non-planar conformer 2 was chosen in this study because the orientation of the carboxyl and amino groups which form an intramolecular hydrogen bond are identical to that in the lowest energy conformers of phenylalanine and tryptophan. (Figure 1.1) [6, 7] Nether phenylalanine nor
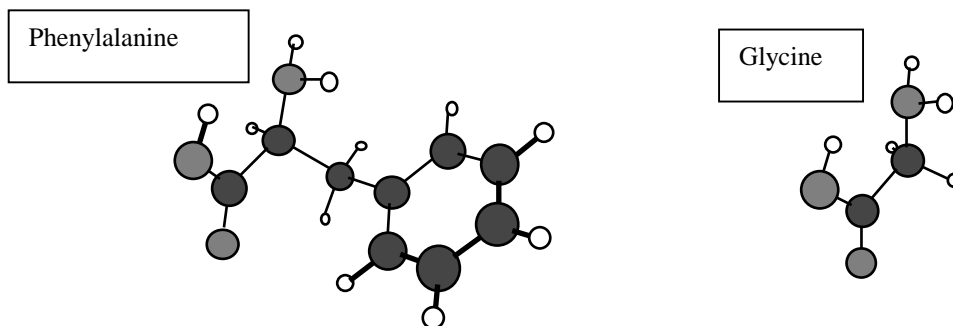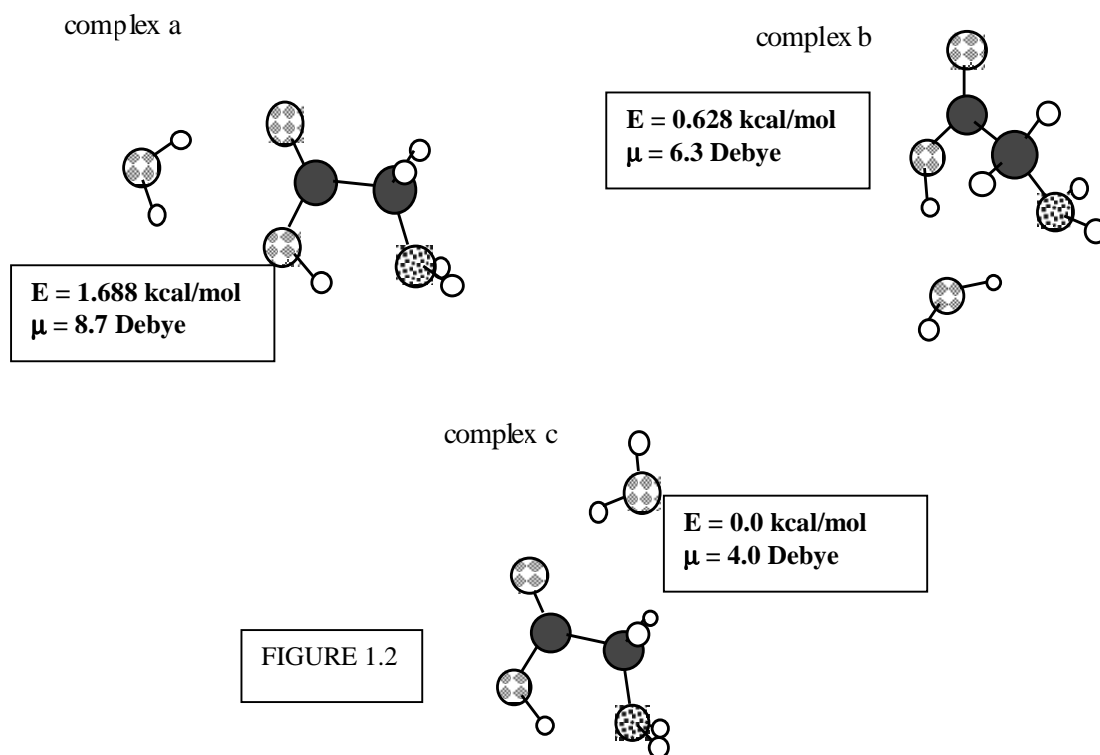

Phenylalanine

Glycine

FIGURE 1.1

tryptophan contain any polar groups in their side chains, so it is reasonable to believe that upon water complexation they will behave in very much the same way as glycine conformer 2.

Complexes of non-ionized glycine conformer 2 with water were studied with the goal to determine vibrational frequency shifts of glycine within the complex. Stationary point structures were located by ab inito methods using the electronic structure package package GAMESS. The geometries of the structures were optimized with no symmetry constraints at the level of restricted Hartree-Fock with second order MØller-Plesset (MP2) perturbation theory. A Dunning-Hay double-ς + polarization basis set was employed, and polarized functions consisted of an additional d function on heavy atoms and a p function on hydrogen atoms. After stationary points were located the second-derivative (hessian) matrix was calculated to insure all frequencies were real and the points did indeed correspond to minima, not saddle points.

complex a

complex b

E = 0.628 kcal/mol
μ = 6.3 Debye

E = 1.688 kcal/mol
μ = 8.7 Debye

complex c

E = 0.0 kcal/mol
μ = 4.0 Debye

FIGURE 1.2

Three complexes of gly2 and 1 water molecule were chosen because they sampled the range of hydrophilic areas on gly2 while also being in position to form bridged structures, which are generally more stable than non-bridged structures. (Figure 1.2) Out of these three, complex c had the lowest intrinsic energy at –359.9515 Hartrees. The geometry of glycine in this complex is almost identical to free glycine, being 0.259 kcal/mol higher in energy. Complex b was only 0.6275 kcal/mol higher in energy than complex c, however its raise in energy is due entirely to its contorted form which is 6.796 kcal/mol higher than free glycine. It is the extremely high binding energy, -14.638 kcal/mol, which pulls the energy down to almost that of complex c. The binding energy of complex c is –8.731 kcal/mol, and that of complex a is –6.841 kcal/mol.[10] For this reason, it is possible that the barrier to de-complex is highest in complex b, and thus lifetime

and population of this form may be longer and greater than for either of the other two. However, confirmation of this speculation would require additional study of reaction paths leading to dissociation of the complex to glycine + H_2O.

The CO and OH stretching modes of glycine and the symmetric OH stretching mode of water showed frequency shifting upon complexation. Other modes (Table 1.1) also show shifting, but these modes are not nearly as intense and the shifting is not so systematic. Obviously, shifting is largely dependent on the position of H_2O, even so, each of the 3 modes listed above redshifts upon complexation. The OH stretch of glycine shows redshifts ranging from $67cm^{-1}$ to $129cm^{-1}$ with large relative IR intensities. The CO stretch shows redshifts ranging from $9\ cm^{-1}$ to $33\ cm^{-1}$. The symmetric OH stretching mode of water by far shows the largest and most unique shifts in relation to position. Complex a shifts $32\ cm^{-1}$, complex c shifts $129\ cm^{-1}$,and complex b shifts $353\ cm^{-1}$. In complex a, the water molecule is bound in a more symmetric manner, through both hydrogens, versus in the other two complexes where water binds asymmetrically through oxygen and hydrogen leaving a free hydrogen. This explains why the symmetric stretch would shift so much more in these complexes. For one-to-one complexes, it seems that the water symmetric stretching modes, which increase drastically in intensity upon complexation, should serve as the best identifiers of a particular complex conformation. The OH stretching frequencies of glycine also show unique shifts and large intensities and thus seem to be the most promising modes to look at in higher ratio complexes.

Next, the space of 2 H_2O + glycine (2:1) complexes was sampled. Three complexes with a water molecule in the position of complex b, and 1 with a water molecule in the position of complexes a and c were chosen. Complex b was chosen due to its high binding energy, and complex c was chosen because it is the lowest energy conformer. To these complexes, additional water

TABLE 1.1. Harmonic vibrational frequencies, cm -1 and IR intensities, Debye^2/amu-Angstrom^2

pure glycine pure water		complex a		glycine + 1 water complex b		complex c		description	
harm	IR	harm	IR	harm	IR	harm	IR		
4056	1.1	4011	1.4	3982	2.2	4005	2.4	H2O asym stretch	
3910	0.2	3878	2.6	3557	18	3781	6.6	H2O sym stretch	
1666	2.1	1711	5.1	1688	1.4	1697	4	H2O bend	
3714	0.4	3719	0.5	3666	0.3	3721	0.5	NH2 asym stretch	
3612	0	3616	0.1	3573	4.1	3620	0.1	NH2 sym stretch	
3559	7.1	3492	9.2	3430	12	3464	9.1	OH stretch	
3225	0.2	3233	0.1	3212	0.4	3242	0.1	CH2 asym stretch	
3152	0.3	3158	0.2	3136	0.5	3170	0.1	CH2 sym stretch	
1860	6.9	1851	7	1827	5.8	1839	7.7	CO stretch	
1446	9.6	1454	9.9	1415	5.7	1468	11	COH	bend
1692	1	1693	1.1	1684	1.1	1690	0.4	NH2	bend
1507	0.2	1502	0.2	1541	0.1	1489	0.1	CH2	bend

molecules were added to previously sampled positions and also previously unsampled positions. (Figure 1.3) The naming of the 2:1 complexes corresponds to that of the 1:1 complexes such that complex AC contains a water molecule in the position of complex a and one in the position of complex c, and BB represents complex b with an additional water added in comparable b space. Complex B2 had the lowest energy at –436.2102 Hartrees. All relative energies are shown in Figure 1.3. All of the complexes containing water in position b remained contorted, only complex BB slightly unwound and glycine's intrinsic energy dropped by ~1 kcal/mol. In complex B2 the intrinsic energy of glycine rose by almost the same amount. Complex BB differs from B2 and all of the other 2:1 complexes because the second water molecule is bound to the oxygen of the first water molecule and the amine group of glycine, versus just glycine. This fact shows up interestingly in the frequency shifting, in that the OH stretch of glycine in BB is blueshifted by 149 cm^{-1} compared to that of complex b. This is an overall blueshift of 20 cm^{-1} from pure glycine.

This is most likely due to the inhibition of the NH stretching mode being locked in by the second H$_2$O (1). Because of this, the NH bond is not as responsive to the glycine OH stretching mode, which it interacts with through the OH of H$_2$O (2) thus, the OH stretch of glycine stiffens. Most other OH shifts remain red and increasing in size. (Table 1.2) The OH stretch of H$_2$O (2) (the initial water from complex b) shifts quite dramatically from pure water at 358 cm^{-1}, 441 cm^{-1}, and 543 cm^{-1}.   This large shifting seems due to a slight correlation with the glycine hydroxyl group hydrogen that is absent in complex AC which only shifts 101cm^{-1}.

TABLE 1.2. Harmonic Vibrational Frequencies, cm-1 and relative IR intensities, Debye^2/amu-Angstrom^2   for 2 water complexes

complex AB		complex B2		complex BB		complex AC		description
4009	1.4	3998	2.5	3994	2.2	4013	1.2	H2O (1) asym str
3981	2.4	3979	2	3973	2.4	4007	3.2	H2O (2) asym str
3878	2.8	3812	3.1	3855	1.6	3873	3.1	H2O (1) sym str
3552	16	3469	30	3367	11	3809	5.3	H2O (2) sym stretch
1713	4.8	1707	1.2	1698	2.6	1712	5.5	H2O (1) bend
1680	1.9	1690	2.9	1664	2.4	1687	1.4	H2O (2) bend
3666	0.3	3636	0.8	3657	0.8	3721	0.6	NH2 asym str
3572	2.4	3527	0.9	3530	1.6	3621	0.1	NH2 sym str
3340	20	3339	9.7	3579	21	3400	11	OH (gly) stretch
3214	0.3	3209	0.4	3204	0.4	3246	0	CH2 asym str
3138	0.4	3137	0.6	3132	0.6	3174	0	CH2 sym str
1815	5.6	1809	5.9	1828	5.4	1829	7.5	CO stretch
1426	4.3	1436	4	1380	6.3	1473	11	COH bend
1687	1.2	1700	0.9	1693	2.6	1692	2	NH2 bend
1539	0.1	1543	0.2	1533	0.1	1486	0	CH2 bend

Compared to complex b, complexes AB and B2 show increased redshifts of the OH frequency of 90 cm^{-1} and 91 cm^{-1}, giving overall shifts from pure glycine of 214 cm^{-1} and 215 cm^{-1} respectively. AC shows a redshift of 154 cm^{-1} from pure glycine for this mode. The intensities of these modes also increase noticeably, more than twofold in some cases. The CO frequencies show smaller shifting from pure glycine in each case, at 45 cm^{-1} , 51 cm^{-1} , 32 cm^{-1}, and 31 cm^{-1} for AB, B2, BB, and AC respectively. It is interesting to note that in the case of complex BB the CO stretch does not show any further redshifting than its parent complex b except a 1 wavenumber blueshift.

complex AB

h2o 2

E = 3.822 kcal/mol
μ = 9.4 Debye

h2o 1

complex B2

h2o 2

h2o 1

E = 0.0 kcal/mol
μ = 4.3 Debye

complex BB

h2o 2

E = 1.506 kcal/mol
μ = 5.4 Debye

h2o 1

complex AC

h2o 1

h2o 2

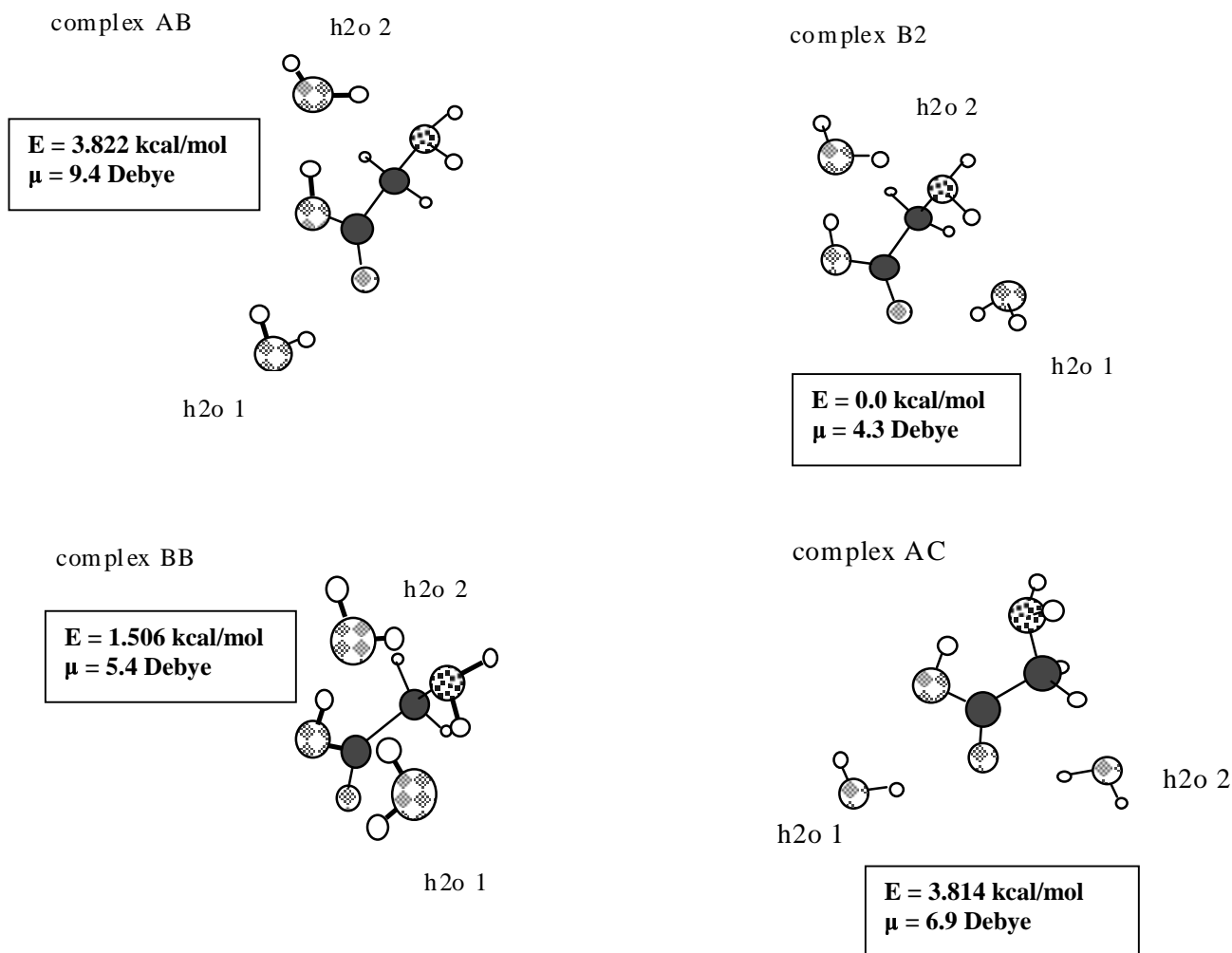E = 3.814 kcal/mol
μ = 6.9 Debye

FIGURE 1.3

These results show that complexation has an observable, while not necessarily predictable, effect on stretching frequencies of glycine and water. How these effects will manifest in higher ratio complexes is uncertain. In the cases of water only being bound to glycine, redshifting was prevalent. However, when a second water molecule is bound to both glycine and an already existing water molecule some frequencies still shift more to the red while in others a halting and even reversal of this trend can be seen. Anharmonic effects are known to play a role in frequency shifting, especially in the case of hydrogen bonding. In previous cases of hydrogen bonding between glycine conformer one and water, anharmonic effects showed a redshift in H_2O stretching modes [9] and in previous studies on the OH stretching frequencies of glycine conformer 2, anharmonic effects also reveal a substantial redshift.[8] It will be necessary to asses this contribution for accurate analysis. Whether addition of more water molecules will inhibit the redshifting trend, or whether it will continue and the exception of a few blue shifting effects will be drowned out by the addition of more water molecules is a curious question that may be of interest in the aid of experiment. The next step in calculation will be to optimize 3:1, 4:1, and perhaps higher water: glycine complexes in order to sample the entire inner shell of solvent accessible area and glycine hydrophilic areas simultaneously. Also, by surrounding these higher complexes with additional layers of water molecules by described effective fragment potentials it will be possible to see how water complexation further affects the vibrational frequencies of glycine.

1   Csaszar A.G., J. Am. Chem. Soc. **1992**, 114, 9568-9575
2   Basch, H.; Stevens, W.J., Chem. Phys. Lett. **1990**, 169, 275-280
3   Jensen, J.; Gordon, M., J. Am. Chem. Soc. **1991**, 113, 7917-7924
4   Jensen, J.; Gordon, M., J. Am. Chem. Soc. **1995**, 117, 8159-8170
5   Lee, K. T.; Sung, J.; Lee, K. J.; Kim, S. D.; Park, Y.D.; J. Chem. Phys. **2002**, 116, 8251-8254
6   Snoek, L. C.; Robertson, E. G.; Kroemer, R. T.; Simons, J. P., Chem. Phys. Lett. **2000**, 321, 49-56
7   Snoek, L. C.; Kroemer, R. T.; Hockridge, M. R.; Simons, J. P., Phys. Chem. Chem. Phys. **2001**, 3, 1819-1826
8   Chaban, G. M.; Jung, J. O.; Gerber, R. B., J. Phys. Chem. A. **2000**, 104, 10035-10044
9   Chaban, G. M.; Gerber, R. B., J. Chem. Phys. **2001**, 115, 1340-1348
10 For a definition of binding Energy see ref. 4